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MIDCOURSE AND HANDOVER IN CRUISE MISSILE DEFENSE

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ABSTRACT

This paper examines the implications of individual system elements on the design and performance of a cruise missile defense. The functional requirements of the CMD system will be discussed, along with options for allocating these functions to the various system elements. The error sources associated with each function will be described and the sensitivity of system performance to them will then be evaluated, for several classes of fire control ranging from high precision to surveillance quality. This analysis will highlight the areas where system performance might be increased by improving the performance of other system components, and the penalty paid in increased complexity of those components. In doing so it will provide insight into the tradeoffs involved in a balanced system design.

Introduction

An effective weapon system architecture for Cruise Missile Defense (CMD) against low altitude targets must include a weapons platform performing command and control functions; a surveillance radar to detect the target; a Fire Control Radar (FCR) to track the target; a communications system to distribute information; and a homing guidance interceptor missile with a high frequency, high resolution RF seeker subsystem for all-weather performance against cruise missiles. The top level system performance requirements must be allocated among these various system elements so that good system performance is achieved while affordability is maintained.

The midcourse missile flight phase is crucial to the prosecution of a CMD engagement. While prelaunch is primarily performed by the tracking radar and the fire control system and terminal is exclusively an interceptor function, midcourse, including handover to terminal, involves nearly all components of the weapon system. All elements of the system must work in concert to enable the interceptor to acquire the target with the terminal seeker at sufficient range-to-go and with small enough heading error to permit a successful intercept. The heading and handover errors are potentially very large as a result of threat, environmental and system error effects. The fire control accuracy, in particular, can range from very precise to highly inaccurate. In the extreme, there is no fire control radar at all, and the system must operate using only surveillance quality data. Larger track errors place more of a burden on the other system elements, and particularly the missile seeker that must support a longer terminal homing range and a more extensive angle search. This may be mitigated somewhat by more sophisticated data processing and communication between the system components. For system balance to be achieved, not only the seeker design but also the radar(s) supporting the engagement and the communication system between the elements of the weapon system architecture, must all be involved and traded off against each other. The tradeoffs are both functional and performance related; how well a function is required to be executed may depend a great deal on where the function is performed.

Midcourse Functional Requirements

A generalized CMD weapon system architecture is shown in Figure 1. Depending on the application and requirements, some of the system components shown may not be needed. Two airborne sensors are shown, one for surveillance and target acquisition and a second for precision track, which, in reality, may be the same radar. The fire control system is located in the launching ship, along with its own organic radar. The communication and registration functions are distributed among the various platforms. Assuming that the threat has been acquired, placed in track, and judged to be hostile and engageable, and that an interceptor has been launched, the system enters the midcourse phase of the engagement. During midcourse the following functions must be performed by one or more of the system elements. Table 1 summarizes the midcourse functions along with potential allocations to system components.

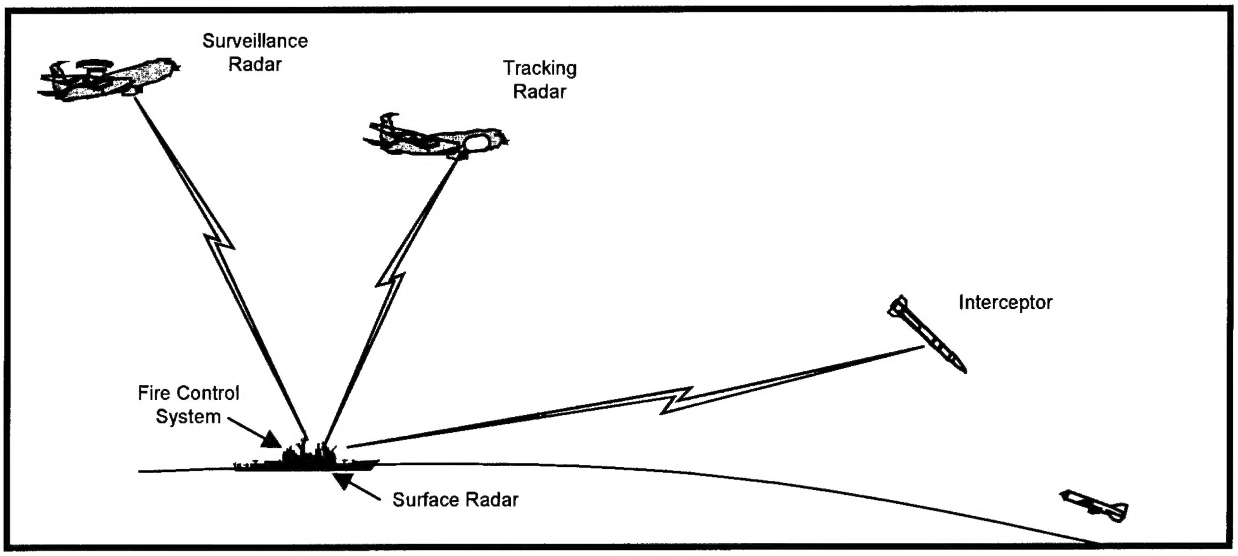

Figure 1 Generalized CMD Weapon System Architecture

Target Track

The target must be continuously tracked to provide midcourse updates to the missile. Target position uncertainty is the primary source of handover error since the "lever arm" of the ratio of intercept range and homing range multiplies the radar track error. Therefore, radar measurement accuracy and data rate are prime elements of system performance. For short range air defense the organic surface radar can perform this function. For longer range area defense against low flying targets, an elevated sensor is required.

Interceptor Track

The interceptor position and attitude must be known in order to determine midcourse guidance commands and seeker search designation. While the missile position uncertainty is generally a much smaller error source than target uncertainty, the attitude uncertainty can be significant since it adds directly to the handover angle error. Modern inertial measurement units are very accurate, but are still subject to initial misalignment and drift errors. The addition of an In-Flight Alignment (IFA) process utilizing uplinked missile position radar measurements or GPS can be used to align the inertial platform and reduce the attitude and other navigation errors. The organic surface radar may be required to track the missile anyway in order to maintain the communication link with the fire control system. If the airborne radar also tracks the missile, it can provide a differential track of the missile and target, and/or provide a means for potentially reducing bias errors with the common track of the missile along with the surface radar track of the missile.

Gridlock / Registration

When a remote sensor, such as an airborne fire control radar tracks the target, means must be provided to register the coordinate systems of the different system elements. Misregistration adds to the target position uncertainty, and is subject to the same lever-arm effect as the radar measurement error. This function can be performed by a dedicated system such as CEC or by the sensors themselves by tracking common targets.

Midcourse Guidance

Midcourse guidance can either be performed by the missile, based upon target position measurements received via the uplink, or by the fire control system which then uplinks the guidance commands to the missile. The choice is complicated in an over-the-horizon engagement by the fact that the shipboard uplink will likely be lost at some point during the engagement, possibly well before acquisition by the terminal seeker. The former option requires that the missile have access to sufficient track data on the target, but has the advantage of allowing a smooth transition to autonomous operation upon loss of signal. The advantages of performing midcourse guidance in the fire control system is that it aids in tracking the missile, and allows the FCS to maintain positive control of the missile.

Communication Link

Communications must be provided between the fire control system and the remote sensor(s), as well as between the FCS and the missile. An additional option

Table 1 Midcourse Functions and Potential Allocations

	System Elements			
Function	**FCS**	**Organic Sensor**	**Remote Sensor**	**Missile**
Target Track		x	x	
Missile Track		x	x	x
Gridlock		x	x	
Guidance	x			x
Comm	x	x	x	x
Designation	x			x
Search				x

for OTH engagements is a direct link between the airborne radar and the missile. This essentially eliminates the loss of the link due to the horizon, but would require a multi-frequency link in the missile, since the airborne radar is likely to be at a different frequency than the organic radar. Bandwidth, data rate and latency are key performance drivers.

Target Designation

Target designation can be performed by the fire control system or by the missile. For OTH engagements, it is highly likely that the uplink will be lost before target acquisition. Therefore if the track filtering is performed in the FCS, it must uplink the designations and error covariances to allow the missile to propagate the cue after loss of signal. It should also be noted that the estimation scheme used for designation would not necessarily be the same as for midcourse guidance.

Search / Terminal Acquisition

Search and acquisition are functions of the missile seeker. The seeker must search the handover uncertainty and acquire the target at sufficient range to go to successfully guide to intercept. The acquisition performance involves a tradeoff between sensor acquisition range and designation accuracy. Larger handover error baskets require longer detection range capability to allow for the search process as well as the longer homing range required by the larger implied heading error.

Performance Factors

Target Track

Radar measurement accuracy can range from fire control quality ($\leq$ 1 mrad) to surveillance quality (up to 10 mrad). In addition, bias errors resulting from mechanical misalignment, calibration errors, etc. can further degrade measurement accuracy. The resulting track accuracy is not only a function of the radar's measurement accuracy, but also of the type of estimator used to filter the measurements and track the target dynamics. The measurement data rate, or update rate, is also a crucial parameter in establishing the target track accuracy. Data rates can vary from 0.1 Hz for surveillance sensors to 10 Hz for precision FCRs. Figure 2 shows the sensitivity of the target track elevation uncertainty to data rate and measurement accuracy for a nonmaneuvering Mach 0.8 target radially inbound to the radar at 100 km downrange. (Note: the radar was assumed to measure range with an 1σ accuracy of 10 feet and range rate with a 1σ accuracy of 4 ft/sec.) The estimator used for this analysis is a 9-state extended Kalman filter with a target-oriented process noise model (ref. 1) that takes into account the ability of air vehicles to maneuver more in the lateral directions than in the longitudinal direction.

Figure 2 illustrates the importance of radar measurement data rate on the size of the target uncertainty. A high data rate will allow even relatively large measurement errors to be reduced to tolerable levels by smoothing. However, a higher data rate requirement represents an increase in radar loading for each track. The resulting total radar loading could become prohibitive when engaging multiple target raids. Data rate enters the handover performance equation in a second way. The curves in Figure 2 show the errors immediately after the track filters are updated with the latest measurements. During search, the error basket must grow between track updates to allow for potential target maneuvers and the uncertainties in the higher order target states. Figure 3 shows this growth as a function of data rate, and demonstrates that this can be a significant issue for low data rate (surveillance) sensors.

Communication Latency

The communication links between the various system elements must have sufficient bandwidth to transmit the required data in a timely fashion. A high latency combined with a low data rate can greatly impact the target track uncertainty. Figure 4 shows an example of the effect of varying amounts of latency on the error basket for a 1 Hz track rate.

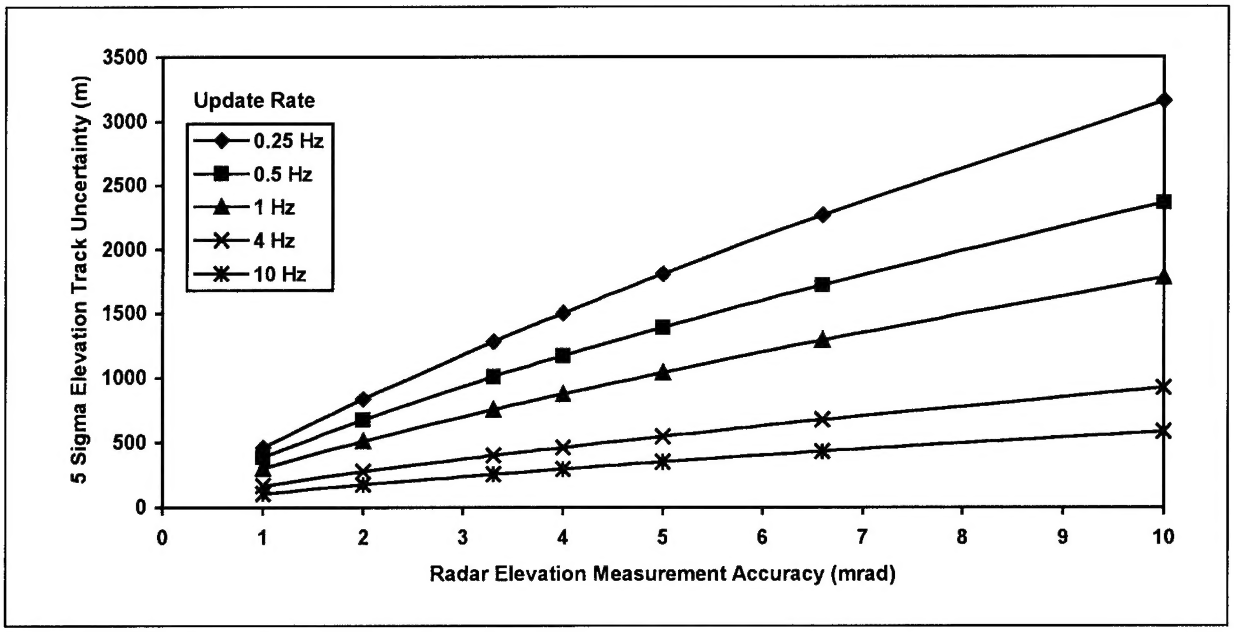

Figure 2 Target Position Uncertainty As A Function Of Radar Measurement Accuracy

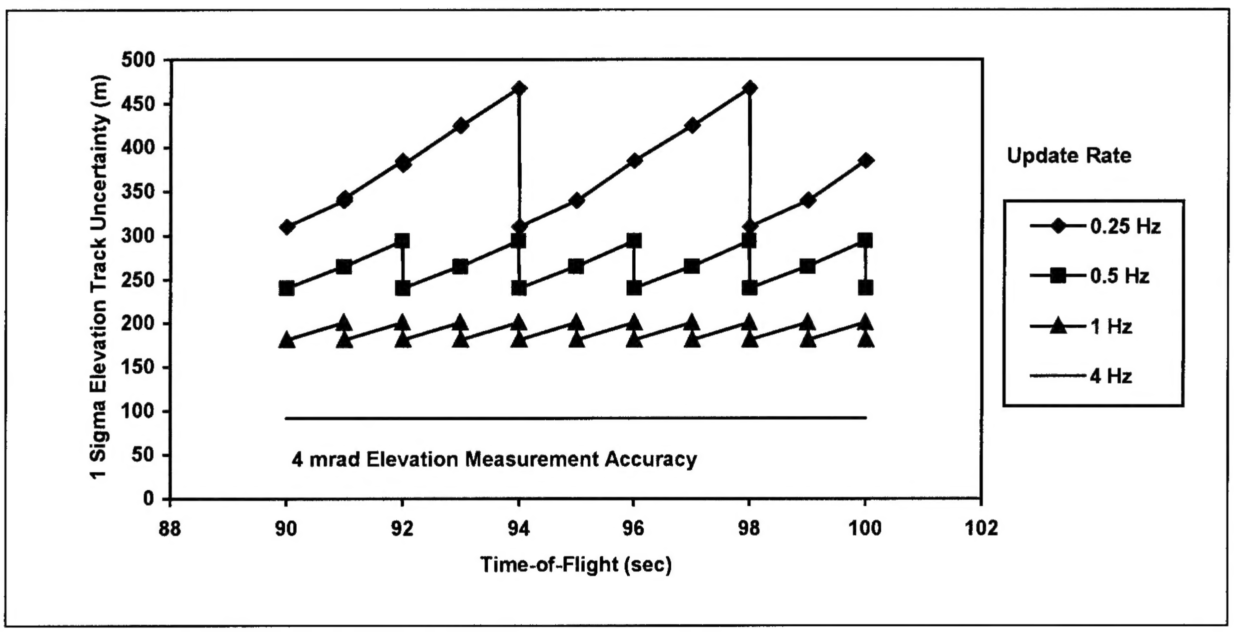

Figure 3 Target Uncertainty Growth Between Measurement Updates

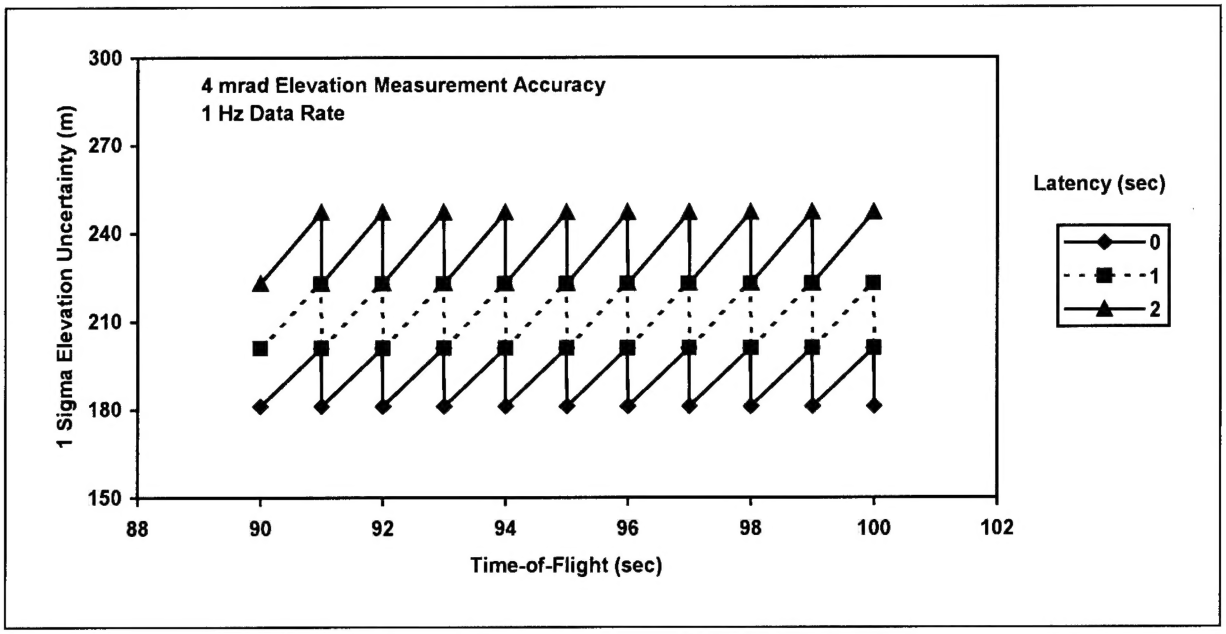

Figure 4 Impact Of System Latency On Target Position Error

Missile Attitude Uncertainty

The missile attitude accuracy is subject to initial prelaunch misalignment and inertial instrument drift during midcourse. The uncertainty can be reduced with in-flight alignment (IFA), using either uplinked radar measurements (if they are accurate enough) or GPS (if it is available). Figure 5 shows an example of attitude uncertainty for 10 mrad (1σ) of initialization error with a 1 deg/hr (drift) INS with 0.1 deg/(root-sec) random walk. This error can be very significant, particularly for narrow beamwidth (i.e. MMW) seeker, since the uncertainty contributes directly to the handover error basket.

Missile Position Accuracy

Missile position uncertainty ideally should be a small contribution to the seeker search basket. The accuracy of the missile position estimate is subject to the same errors as the missile attitude. Figure 6 shows an example of missile position error as function of range for: 1) inertial navigation only (assuming the INS package mentioned earlier); 2) inertial navigation with IFA provided by the surface radar track of the missile, assumed to be better than 1mrad; and 3) GPS. It is apparent that midcourse guidance and handover using the missile's INS only are not very useful except at very short engagement range. The position accuracy attainable using IFA is approximately equal to the accuracy of the sensor position measurements used to provide the in-flight updates. Therefore a FCR quality track of the missile provides missile position uncertainty suitable for midcourse guidance and handover, but a surveillance quality track likely does not. Fortunately, most weapon systems include a precision organic fire control radar, which can perform this function. GPS of course provides missile position accuracy that is for all practical purposes error free.

Gridlock / Registration & Bias Reduction

For systems with remote sensing (i.e., ADSAM), bias errors between the system components must be accounted for in the handover basket if the target and missile are tracked by different sensors. The errors factor into the total handover uncertainty in the same way as the track radar errors, except that filtering cannot reduce them. The bias errors can, however, be estimated and their impact on the handover basket reduced by tracking a common object. In this case, the airborne and shipboard radars would both track the missile.

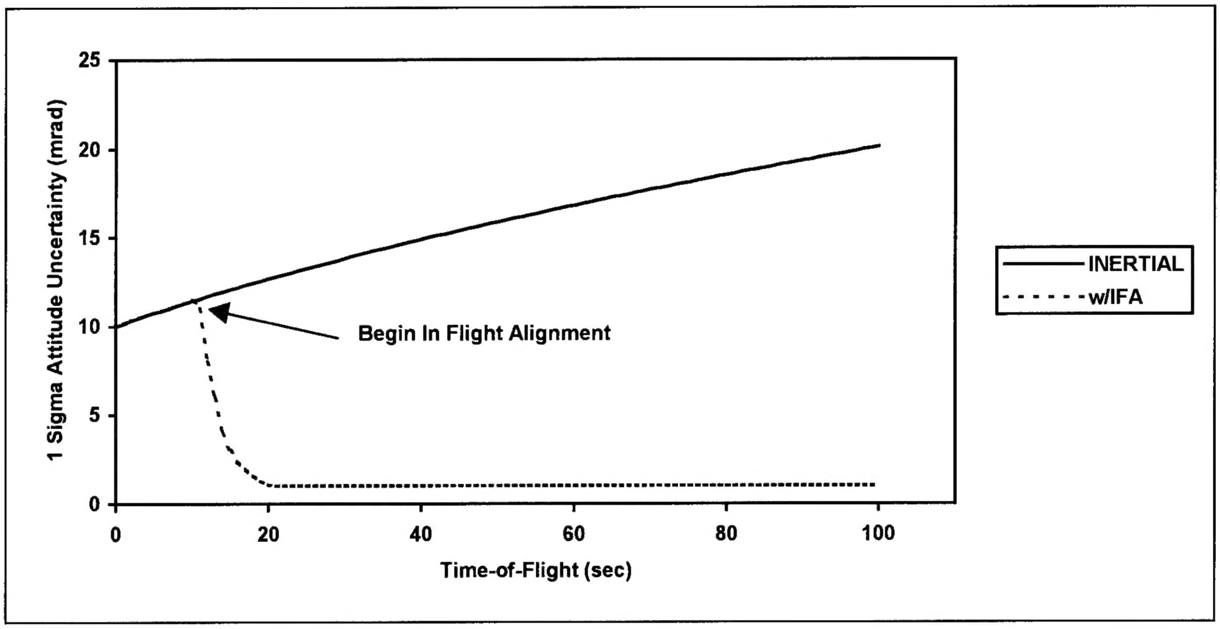

Figure 5 Missile Attitude Uncertainty With and Without In-Flight Alignment

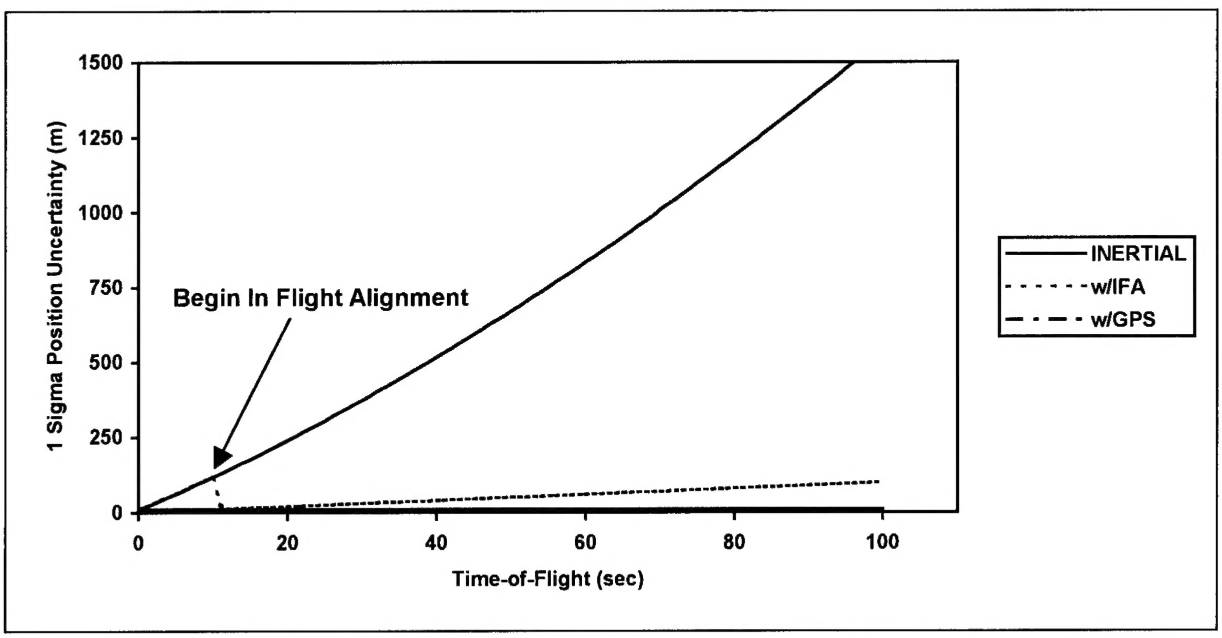

Figure 6 Missile Position Uncertainty With and Without In-Flight Alignment

Search and Acquisition

The missile seeker must search out the handover basket and acquire the target with sufficient range to go to permit a successful intercept. The seeker acquisition capability is determined by the detection range or sensitivity, and the ability to quickly scan the angle, range and doppler uncertainties. While the detection range is a function of many factors, the requirement can be defined in terms of the range where a unity signal-to-interference ratio is obtained in a single coherent processing interval (R_0) in free space. This not only allows the sensitivity to be compared using a single parameter, it obviates the need for a specific description of the threat. Target radar cross section is a factor in R_0, so if the seeker performance is known, the R_0 requirement can be used to determine the minimum target RCS that can be successfully engaged. The CPI length is defined by the seeker data rate and the number of CPIs noncoherently integrated. Noncoherent integration permits the use of frequency diversity to improve the detection probability against fluctuating targets. This becomes more important as the angle uncertainty grows resulting in fewer search revisits and detection opportunities. For the analysis presented in this paper, a data rate of 50 Hz, with four dwells non-coherently integrated, has been assumed.

The second factor in target acquisition is scan capability. This is a function of the seeker beamwidth and the rate at which the beam can be moved through the uncertainty volume. A larger beamwidth would appear to have an advantage in this regard, however the additional angular coverage comes at a cost of reduced gain and therefore reduced R_0. In this analysis, beamwidth is treated parametrically, using values of 2, 8 and 14 degrees. This covers the range from larger diameter missiles at millimeter wave frequencies to smaller missiles at X-Band. Ideally the seeker would search a new beam position during each radar cycle, covering the angle uncertainty as quickly and efficiently as possible. This is can be done if the antenna is an electronically scanned array (ESA) where the beam may be repositioned between cycles. A gimbaled antenna, in contrast, must be in continuous motion and is therefore subject to gimbal rate and acceleration limitations. The scan patterns and search algorithms then become factors as well. The search process is application specific and involves many parameters including scan rates, beam overlap, gimbal response and scan pattern details. An exhaustive examination of all these parameters is beyond the scope of this paper.

Figure 7 shows the R_0 requirement as a function of error basket size and seeker beamwidth for the two basic scan patterns that are typically employed with a gimbaled seeker: the spiral and the raster scan. These curves were generated assuming a closing velocity of Mach 3 and a missile that incorporates a modern, highly responsive autopilot resulting in a homing range requirement on the order of 1 nmi for moderate heading error. The wider beamwidths result in a reduced R_0 requirement for large uncertainty volumes however the range advantage is very nearly equal to the reduction in two-way antenna gain implied by the wider beamwidth. Thus in clear weather the search performance is not a strong function of the radar beamwidth itself. However, to the extent that a narrower beamwidth implies a higher frequency, the wide beam-low frequency seeker will have the advantage of lower propagation losses, which will be significant when comparing performance of X-Band and MMW seekers in the rain.

The performance of the two search patterns is similar for moderate error baskets, with a slight advantage for the raster scan, as the volume becomes larger. The real advantage is seen, as the error basket becomes more elliptical, in Figure 8. In these curves, the elevation error is equal to the aspect ratio times the azimuth error, which is 100 m (1σ). The larger R_0 requirement for the spiral search is due to the fact that the number of beams in a search frame is essentially the same as would be required if the volume were circular with a radius equal to the major semiaxis of the ellipse. Since the azimuth and elevation errors are typically unequal due to radar configurations and multipath effects, the raster scan will generally provide improved handover performance, as long as the gimbal dynamics are sufficiently robust. An additional benefit of the raster scan is that it can be easily "clipped" at the surface, assuming that the missile knows its altitude. To take full advantage of the performance improvement afforded by the raster scan requires that the scan be aligned with the largest axis of the uncertainty volume, which in turn requires the missile to know the full covariance matrix of the target errors. If the track filtering is performed in the missile, this is not an issue. However, if the filtering is performed elsewhere and the designation data uplinked to the missile, the full covariance matrix must be accommodated in the uplink message. An additional consideration in using a raster scan is that the need for rapid scan reversals will require higher acceleration capability and additional power consumption in the gimbal system.

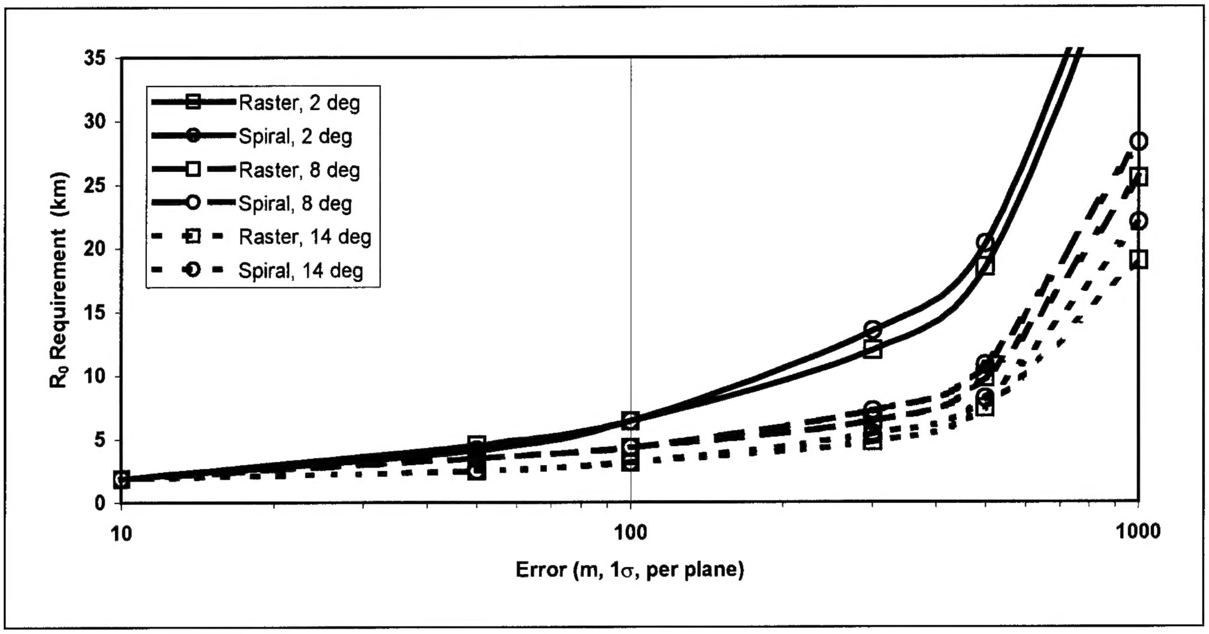

Figure 8 R_0 Requirements As A Function Of Angle Error Basket

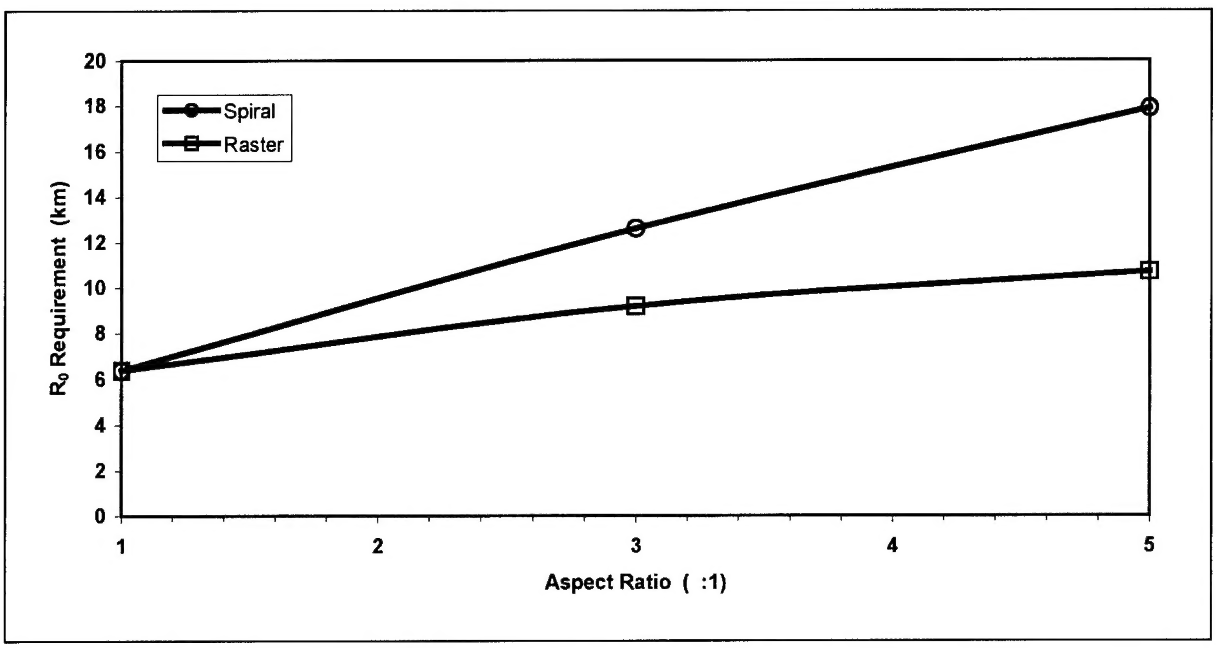

Figure 9 R_0 Requirements As Function Of Error Aspect Ratio

The third factor in acquisition performance is the potential need for range and/or doppler search. If the range-doppler uncertainty becomes excessive, multiple PRFs may be required at each beam position to uncover the eclipsed ranges and doppler blinds. If this is the case, either the available beam dwell time must be split between the two (or more) PRFs (e.g. two CPIs each) or the scan rate must be reduced to allow for multiple dwells per beam. In either case, search performance will suffer. To minimize the range-doppler uncertainty, the range and doppler baskets must be tailored as a function of beam position. As in the raster scan orientation, the range-doppler tailoring requires full covariance information to implement. For generality, it will be assumed in the analysis presented in this paper that a single PRF is sufficient to cover the range-doppler uncertainty. This is because the range-doppler coverage is a function of a variety of system-specific parameters, including frequency, velocities, available PRF ranges and processing architectures.

Performance Sensitivities

To illustrate some of the trades encountered in defining a weapon system architecture, the design of an air directed surface-to-air missile (ADSAM) system is considered. The airborne fire control radar (AFCR) will be allowed to vary from high precision to surveillance quality. The missile seeker R_0 requirement will be used to illustrate the impact on system performance of the AFCR capability and any system improvement options. An increase in R_0 can be interpreted either as a reduction in capability (e.g. a higher minimum engageable target RCS) or an increase in the sophistication and cost of the RF seeker. To limit the range of system parameters, the following assumptions will be made: 1) the system is designed to engage targets at a range of 100 km from the AFCR; 2) the AFCR elevation and azimuth errors are equal; and 3) the missile seeker beamwidth is 2 degrees, corresponding to a high resolution MMW seeker.

One approach to the problem is to employ the AFCR to track both the target and the missile and to provide differential measurements to the interceptor. Beside the relative implementation simplicity, the primary advantage to this approach is that it eliminates any bias errors between the missile and target tracks, at least to the extent that the errors are independent of AFCR line-of-sight. The total handover basket size is shown in Figure 9, as a function of AFCR capability. The combination of measurement accuracy and data rate will clearly have a significant impact on the handover capability of the weapon system as shown in Figure 10. When precision radar measurements (1 to 3 mrad) are available, this system provides robust handover capability with only a moderate update rate. As the measurement error grows a higher data rate or a more capable seeker is required to maintain system performance. If the measurements are of surveillance quality (3 to 10 mrad), a very high data rate is required to avoid either an unacceptable loss in capability or a prohibitive seeker requirement. Unfortunately, a low data rate is more typical of a surveillance radar.

If the combination of radar accuracy and data rate do not provide acceptable differential track performance, other means of reducing the handover baskets must be found. The error baskets in Figure 9 are essentially the RSS of equal target and missile position errors (with some addition due to missile attitude error). Therefore improving the missile location accuracy can potentially reduce the handover baskets by up to 40 percent per plane. This may be accomplished using either on-board GPS navigation or precision track data from the organic system fire control radar. The disadvantage in providing an alternate source of missile data is the introduction of bias errors between the two platforms. Bias errors include the misalignment of the various system platforms, as well as any measurement biases in the sensors. If a surface-based radar is used for missile measurements, a second issue is that for an over the horizon engagement the uplink, and thus the missile position updates, will be lost at some point. However, this will happen late enough in the engagement that the INS drift should be acceptable.

Figure 11 illustrates the effect of missile errors on total handover basket size as a function of target designation error and bias error. The plot shows the percentage growth in the error basket, above that for the target uncertainty alone. The reference line at 41% represents the differential track case, while the arrows indicate some representative combinations of radar accuracy and data rate. The curves labeled GPS are for on-board GPS navigation, while the IFA curves represent the case where the missile position is derived from measurements by the surface fire control radar. A radar measurement accuracy of 1 mrad is assumed. The figure demonstrates the strong dependence that bias error exerts on the utility of improved missile track data. Unless the bias errors can be kept very small, differential track will provide superior performance with a precision fire control radar. Conversely, with surveillance quality track data, precision missile data will offer improved performance even with significant bias errors.

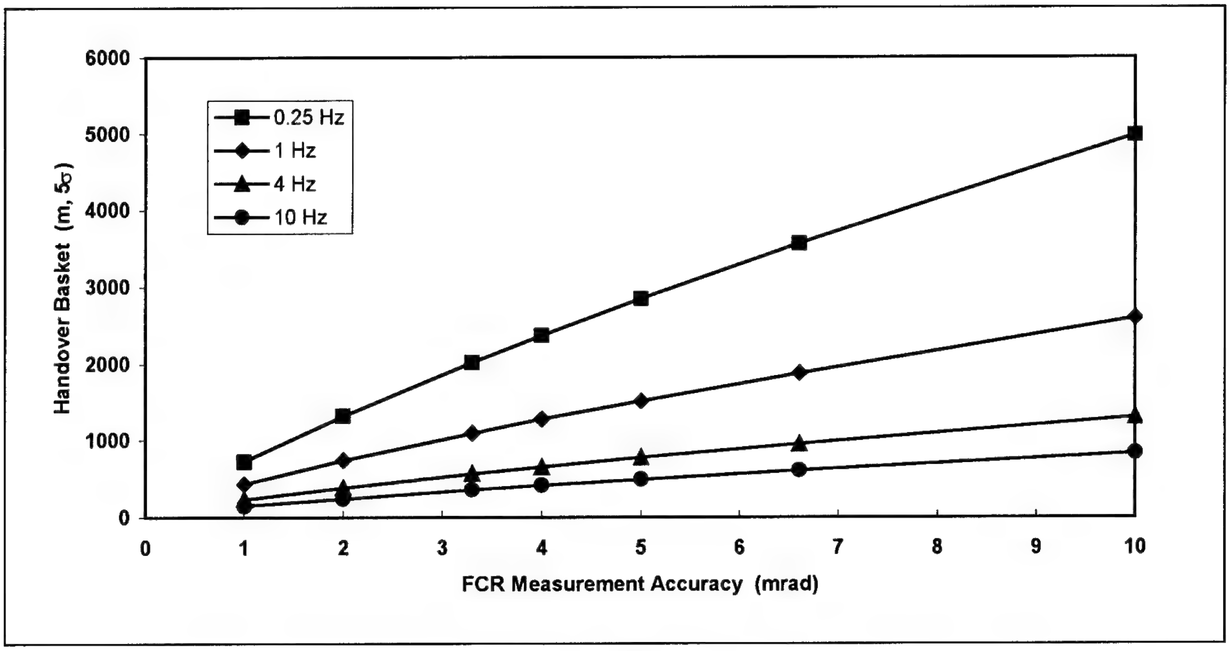

Figure 9 Handover Basket Size For Differential Track Of Missile And Target

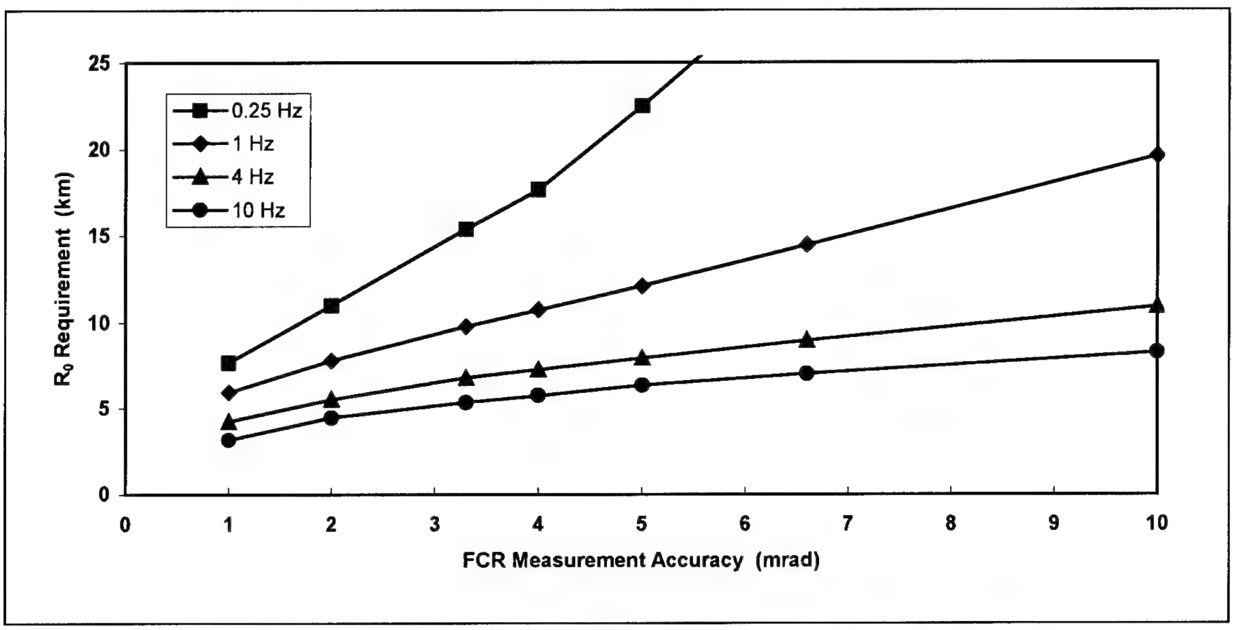

Figure 10 R_0 Requirement For Differential Track Of Missile And Target

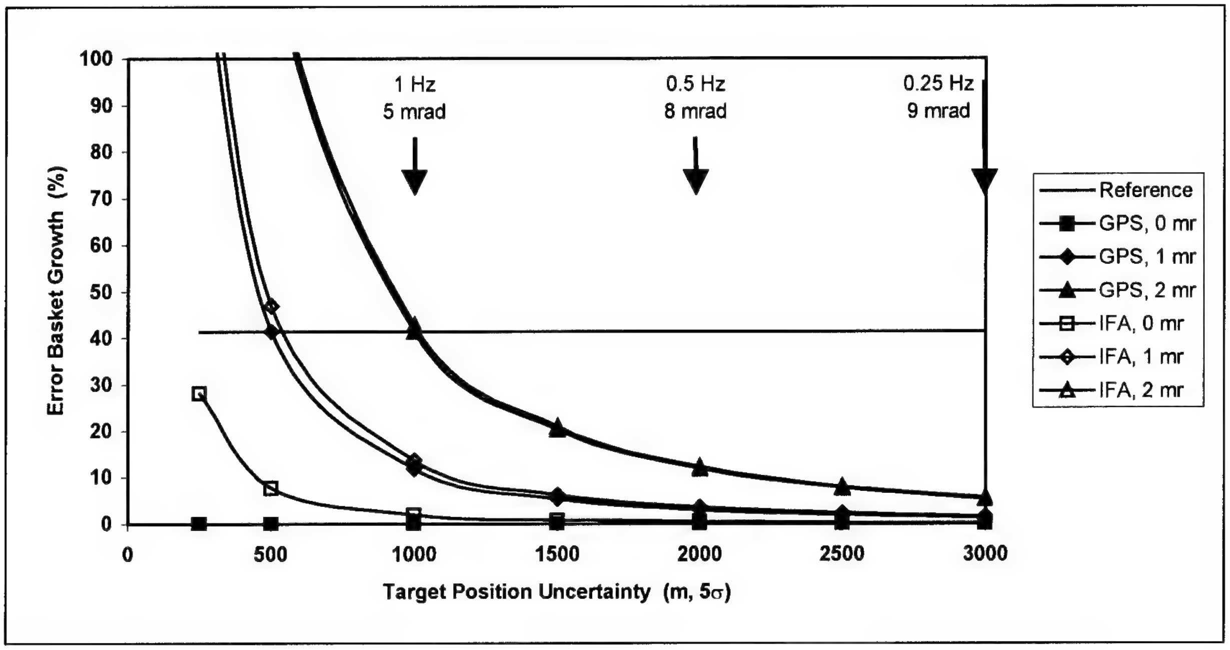

Figure 11 Impact Of Missile Position Accuracy On Handover Basket Growth

If the intrinsic bias errors in the system are unsuitably large, it may be possible to estimate and compensate for them by tracking a common target (the interceptor) with both sensors. Note that this option is not available for on-board GPS navigation. The efficacy of bias compensation is dependent on the extent to which the biases are common to both the missile and target measurements. Since the angular difference between the missile and target will be small in the latter stages of the engagement, it should be possible to obtain a good bias estimate. Figure 12 shows the potential for angle bias estimation as a function of radar measurement accuracy and update rate. For this example, a simple 2-state Kalman filter was designed to track the bias. Also, it is assumed that 40 seconds of common track measurements on the missile are available, and that the surface radar track of the missile (e.g., beacon track) is much better than the airborne radar.

The cost of the bias compensation process is the requirement on the AFCR to track both objects, which increases the resource loading on the radar. An example of the improvement that may be obtained is shown in Figure 13, which is the R_0 requirement for a system using bias estimation and compensation. The residual bias errors are as shown in Figure 12, except that a maximum of 2 mrad is assumed to account for the system gridlocking element. In these curves, differential tracking is maintained where it results in smaller uncertainty baskets. Comparison with Figure 10 shows that an improvement of 6 dB or more is possible for cases of large target uncertainties.

To summarize some of the system component interactions and tradeoffs, Table 2 shows representative data for the ADSAM system assuming three different types of airborne radar. The first is a precision track radar, capable of very accurate measurements at a high data rate. This radar provides the highest level of performance, with the least complex implementation. It is also sufficiently robust that the data rate can be cut in half if needed, with only on the order of 2 dB reduction in system performance. At the other end of the spectrum is a surveillance radar, which provides coarser measurements and, more importantly, a much lower data rate. This system provides over 20 dB less performance than the tracking radar, even with precision missile track data and bias compensation. A system based upon such a radar will require that all other components (i.e. the missile, surface radar, communications, etc.) be as sophisticated as possible. In between, is a multifunction radar, which provides the same measurement accuracy as the surveillance radar, but is capable of doing so at a much higher data rate. This might in fact be a surveillance radar, which is able to stop scanning while prosecuting an engagement. Because of the high data rate, this system is much more capable than the surveillance radar, and thus allows for more room to trade performance versus complexity.

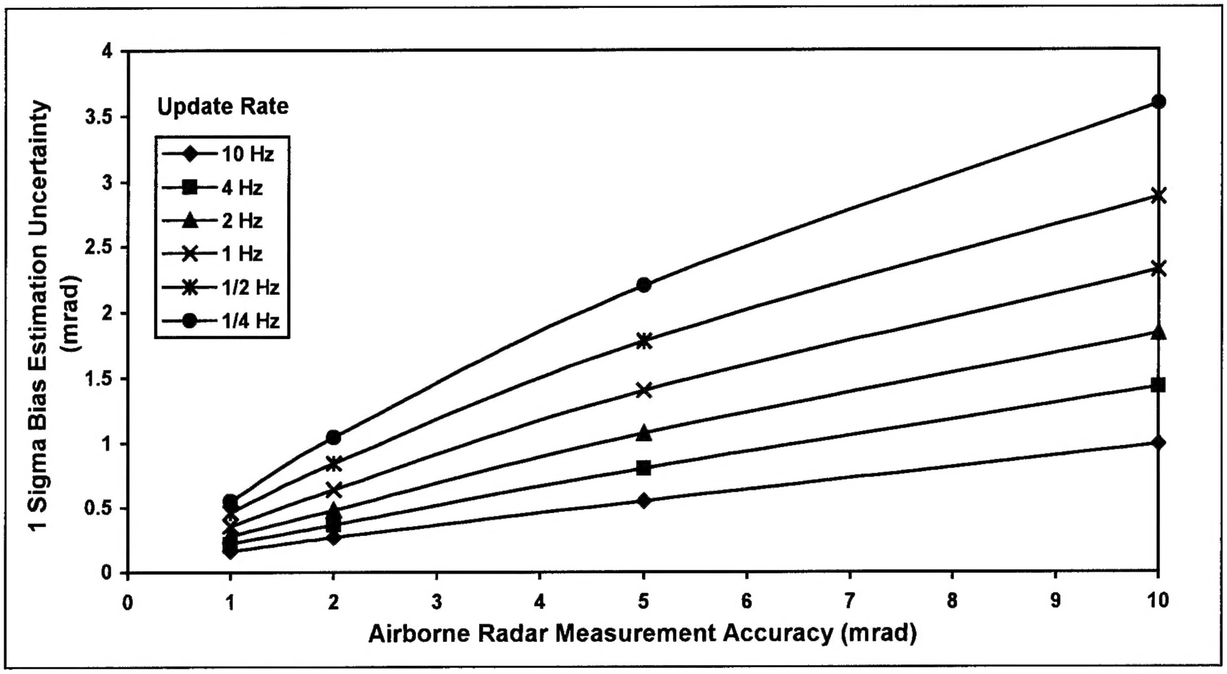

Figure 12 Angle Bias Estimation Uncertainty As A Function of Radar Measurement Accuracy

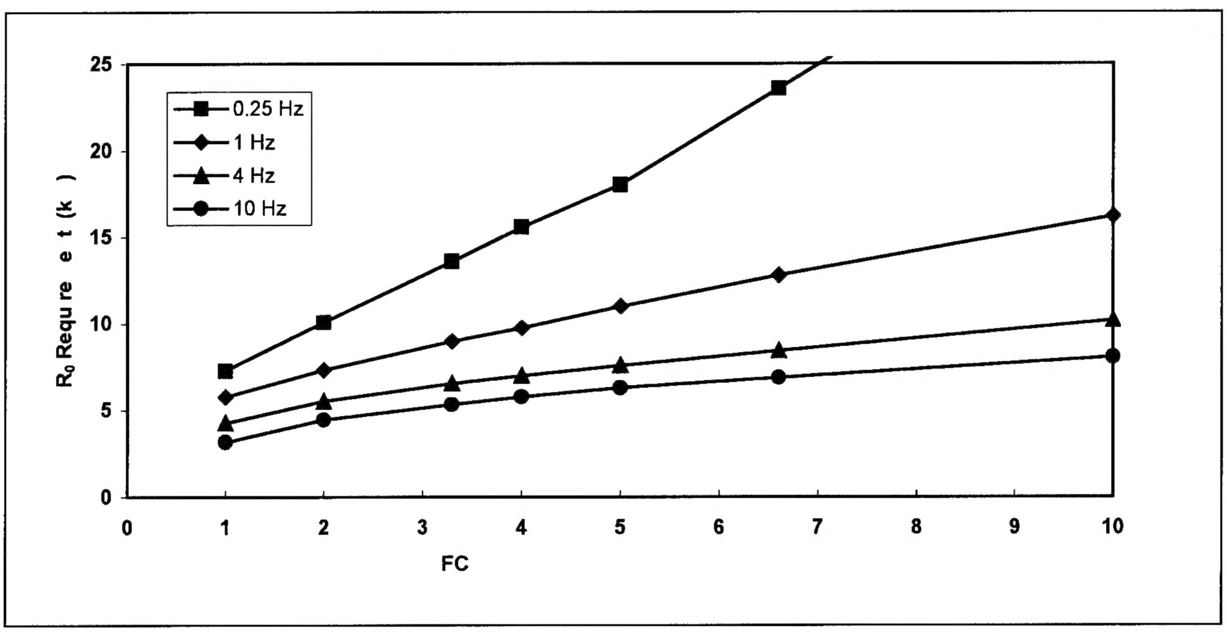

Figure 13 R_0 Requirements For System With Bias Estimation And Compensation

Table 2 Notional System Comparison

FCR Type	Accuracy (mrad)	Data Rate (Hz)	Seeker R_0 (km)	System Implementation	Possible Complexity Tradeoff
Precision Track Radar	2	4	5.5	Differential Track	2 Hz Data Rate: -2 dB
Multifunction	6.6	4	8.4	AFCR Target Track Precision Missile Track Bias Comp.	Differential Track: -1 dB
Surveillance	6.6	0.25	20	AFCR Target Track Precision Missile Track Bias Comp.	None

Functional Allocation

Tables 3 and 4 present the optimum allocation of certain key midcourse and handover functions between the FCS and the missile for the notional systems as described in Table 2. The optimal allocation has been defined by considering two factors: uplink loading and system performance.

For clarification, target state estimation (TSE) refers to the function that processes the associated radar measurements of the target and produces estimates of target position and velocity suitable for midcourse guidance and seeker handover. Missile track for the FCS is similar to the TSE for the target. Missile track for the missile refers to the missile's navigation function with the possible inclusion of IFA.

In all cases, bias compensation is best suited to be performed in the FCS, since this minimizes the uplink loading. Missile track data (measurements and covariances, including time stamping) from the remote sensor would otherwise be required to be uplinked to the missile.

System with Precision Track Radar

For the "Precision Track Radar" system with an accurate differential track, the FCS computes midcourse guidance commands and relative missile-to-target seeker designation commands and uplinks these messages to the missile. The missile's processing in this case is very light, and the uplink loading is minimal.

Table 3 Optimal Functional Allocation for "Precision Track Radar"

	System Elements	
Function	**FCS**	**Missile**
Target State Estimation	x	
Missile Track	x	x
Bias Compensation	x	
Guidance	x	
Designation	x	
Search		x

System with Surveillance Quality Radar

For the case where the remote sensor or FCR is of "surveillance" quality, it becomes necessary to shift functionality to the missile. The seeker requires the full set of target and missile states and covariances in order to propagate properly the states between updates and to appropriately tailor the search processes. The additional uplink data required for this purpose is justified to avoid the system performance penalty in utilizing the remote sensor's differential track. The issue then becomes how best to provide the needed data to the missile seeker. If the TSE is onboard the missile, then only the radar measurements of the target (e.g., 9 parameters: 4 measurements with covariances and a time stamp) need to be uplinked to the missile. Otherwise, the uplink message must include the output from the FCS TSE process which, at a minimum, are the target's position and velocity vectors (6 parameters), and the covariance matrix (at least the 6 principal parameters plus 6 cross terms) and a time stamp, for a total of at least 19 parameters. In addition, this option does not include any information about target acceleration states, that could be used to optimize the handover process.

The allocation of midcourse guidance and seeker designation follows logically from the decision on the location of the target state estimation. With this capability in the missile, having the missile generate its own midcourse guidance commands and seeker designation commands is straightforward.

Table 4 Optimal Functional Allocation for "Surveillance Quality FCR"

	System Elements	
Function	**FCS**	**Missile**
Target State Estimation	x	x
Missile Track	x	x
Bias Compensation	x	
Guidance	x	x
Designation		x
Search		x

Conclusion

This paper has presented an overview of the component tradeoffs involved in designing a cruise missile defense system. In particular, the fire control radar has been shown to be the key determinant of weapon system performance. As the FCR varies from a precision tracking radar to a surveillance quality radar, more sophisticated processing techniques and a more advanced missile seeker are required to maximize system capability.

References

1. Blair, W. D., and Parker, J. D., ``Use of target-Oriented Process Noise in Tracking Maneuvering Targets", *29th Annual Allerton Conference on Communications, Control and Computing*, October 1991.

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PART I

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